Design and Control of Multi-Location Distribution Systems

Donald B. Rosenfield
Visiting Associate Professor
M.I.T. Sloan School of Management

Senior Consultant
Arthur D. Little, Inc.

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Introduction

This paper examines the issues in the design and control of multi-location distribution systems. Multi-location distribution systems involve the procurement of merchandise or raw materials from vendors; the transport of the same to plants, warehouses and distribution centers, the stocking of finished goods or merchandise, and the delivery of these goods to customers or retail outlets. Some of these distribution systems use distribution centers, which consolidate and distribute merchandise to capitalize on the economies of scale in transportation, and others use warehouses, which serve to stock goods and possibly consolidate deliveries.

The design and control of these systems involve a range of questions involving facilities, inventories, product flows and transportation. In addition, control of the movements and storage of goods require a greater level of sophistication than simple single installation retail outlets or manufacturing operations.

In addition to the obvious operational questions of multi-location distribution systems, the basic logistics choices have important strategic implications. The strategic implications of logistics choices have been examined by Shapiro, [1] by Shapiro, Rosenfield, and Bohn, [2], Shycon and Sprague and, with respect to facilities choices, by Hayes and Wheelwright [4]. A firm can gain a competitive advantage using distribution and its network of facilities. There are quite clearly significant strategic differences, for example, in operating a large number of distribution facilities and in operating a small number of facilities. A firm might compete by offering high service (large numbers of facilities) or low cost (smaller number of facilities.) By understanding the distribution and logistics options available and the nature of the marketplace, a firm can better design its distribution network.

In using multiple distribution facilities there are a number of important questions that must be answered. These include:

- number and location of facilities
- service level
- size of facilities
- assignment of products and markets to facilities
- design of system during growth stage
- echelon design
- inventory control and coordination

The number and locations and sizes of both manufacturing and distribution facilities have obvious impacts on both cost and service, and the goals for service are strategically important. Once a network is designed, there are also complex issues of product and market assignment. For an expanding firm, there are the important issues of the growth of the logistics system. Firms can alternatively grow simultaneously in all regions of the country, requiring a full-scale distribution network, or grow sequentially region by region, requiring only a staged growth of the distribution and manufacturing network. The echelon design is a key issue for service and inventory management. Many firms have several stages, or echelons, of inventory and distribution. A national plant or warehouse may supply a regional warehouse which may in turn supply a local warehouse and possibly even a representatives' trunk! Each of these is an echelon. In the computer industry, where specific critical spare parts may be required only occassionally, individual parts may be stored at any one of several echelons. For these types of distribution systems, the number of echelons can be a crucial design factor.

The echelon design leads to the final issues of inventory allocation, control, and coordination. While multiple echelons may not be common, most large businesses maintain two echelons where central plants and warehouses facilities may supply satellite warehouses. How to distribute and control inventory among the locations are important design and management questions.

In order to provide a focus and framework for addressing the design and control of multi-location distribution networks, we focus in this paper on what we view as the four key questions:

- number of distribution facilities
- location and size of distribution facilities
- deployment of inventory among distribution facilities in a two stage (plant and distribution center) system
- control of inventory among facilities

Number of facilities is clearly a key design issue. Given the number of facilities, sizing and location are dependent on many characteristics of the business. These factors include sourcing factors, locations of markets, economies of scale in manufacturing and distribution, and locations and capacities of existing facilities for an expanding firm. Inventory deployment and control are crucial because of the nature of manufacturing and distribution. For many nationally or regionally based businesses, the number of manufacturing facilities is less than the number of distribution facilities [4]. As a result, plants will generally serve as combination plants and distribution centers, which will in turn supply the additional distribution centers. For firms with extensive distribution networks, there will hence be two stages or echelons. The key inventory management issue is the allocation of inventory between the two echelons. That is, should inventory be concentrated at the first, or plant stage, of the system with modest stock

levels at the second stage, or should be inventories be concentrated at the second, or warehouse, stage of the network, with minimal staging stock at the plant stage of the system. In addition, once inventory is allocated among the two stages, how should it be controlled? Standard methods for controlling inventory at a single location, such as order point systems, may not be sufficient for two-stage networks where there are complex interactions between the two stages. Methods such as Distribution Requirements Planning [5] have been suggested for handling these more complex systems. In any case, a different framework or approach is required for a multi-stage network.

This paper presents an overview of these four key questions in the design and control of multi-location distribution networks, and identifies the different situations which will cause different firms to approach design questions differently.

Number of Distribution Facilities

There are several factors that impact the choice of the number of distribution facilities. These include

- distribution costs
- customer service levels
- growth patterns of business
- number and location of manufacturing facilities

There is an obvious relationship between the number of distribution facilities and both distribution costs and customer service. With additional facilities, customer service improves. While inventory investments and facilities investments increase, transportation costs may decrease as described as follows, due to the economies of scale in the costs of individual transportation loads. Economies of scale dictate that full loads cost less per unit than partial loads. If a manufacturing firm is paying for outbound

transportation costs (from distribution centers or warehouses to customers, which may be in small loads), transportation in consolidated loads to warehouses or distribution centers will give more economic transportation to the inbound (to warehouses or distribution centers) portion of the delivery. With additional distribution centers or warehouses, facilities are, on average, closer to the customer, the inbound portion of the delivery increases, and total transportation costs can decrease. In a retailing business, where loads from vendors are typically in small loads and loads from distribution centers to stores are in consolidated loads, a distribution network with several distribution centers will provide a similar economic advantage. In both situations, however, as the number of distribution centers substantially increases, it may not be possible to deliver full loads to distribution centers or warehouses (for a manufacturing firm) or from distribution centers (for retailing chains).

In the situation where the customer is paying for transportation from the distribution center or warehouse, facility and inventory costs quite clearly increase as the number of facilities increases. Transportation costs may also increase, or they can stay approximately the same. With an increase in the number of facilities, some distribution centers or warehouses may be closer to plants (decreasing inbound costs) and some may be farther away (increasing inbound costs). The overall effect is in general not clear but costs should not vary substantially with the number of facilities. Some specific quantitative results for these types of relationships are presented below.

Corporate growth is another important factor in the determination of the number of facilities. Companies that are expanding geographically need to add distribution facilities for both economic and service reasons. A firm may expand by slowly expanding its geographic base or by attempting to expand simultaneously in several locations on a small scale. The latter approach may

be problematic in terms of economies of scale of distribution costs. For a broad-scale geographic expansion, Hayes and Wheelwright discuss the requirement of establishing "beachhead plants" for the associated manufacturing network. A growth strategy also critically affects location and size of facilities, and the topic is more extensively discussed in the next section.

A fourth factor that affects the number of distribution facilities is the nature of the manufacturing network. Distribution facilities are often located adjacent to, or are designed as part of, a manufacturing plant. The design of a manufacturing network is not the focus of this paper, but it is important to note that manufacturing facility location is often based on a different type of analysis than the analysis of the distribution. This may include manufacturing economies of scale, labor and tax questions, location of key suppliers or raw materials, and plant focus in terms of products and process. In any case, the design of the distribution network needs to take into account the design of the manufacturing network.

For most nationally-based manufacturing firms, as noted, the ideal number of distribution locations exceeds the ideal number of manufacturing locations. The distribution system design issue is therefore to determine the best number of warehouses or distribution centers given the limited number of manufacturing locations. In general, the two problems are related, but given the additional issues inherent in the manufacturing network design, a decoupling is often feasible, and we concentrate on the separate design of the distribution network.

To deal with the various issues inherent in the determination of the number of distribution facilities, we consider the two primary questions concerning the number of distribution facilities (distribution centers or warehouses):

- How do costs vary with number of distribution facilities?
- What is the relationship between service and cost as the number of distribution facilities is varied?

The discourse that follows is based on a manufacturing firm with a fixed but small number of plants. An analogous set of conclusions can be reached for a retailing chain.

To answer these two questions, one can make some simplifying assumptions about the distribution of demand and the locations of distribution facilities that, while not always valid, should not compromise the determination of the appropriate number of facilities. Specifically, if one assumes that 1) demand is uniformly distributed 2) each distribution facility is located in the center of a region that it supports and 3) the area of each distribution facility territory is equal, then some general results are obtainable.

Consider a network of an arbitrary number of distribution facilities N. Each facility covers l/N of the total area of the business. It follows that the outbound transportation time (from the distribution centers to customers) will be proportional to the square root of l/N, since this is the linear dimension of area corresponding to each distribution center. These outbound movements will generally be LTL movements, and assuming LTL costs are linear functions of distance, variable outbound costs will also be proportional to the square root of 1/N. While LTL costs often vary substantially, in general the linear assumption is reasonable [6]. As noted, up to a certain number of distribution facilities inbound costs should not vary with the number of facilities, since the average distance from the central plant or plants will not change. (With more facilities, some facilities will be closer to a central plant, and some will be farther away.) However, as the number of distribution facilities reaches a certain level, it is not possible to obtain full transit loads inbound.

How will facility and inventory costs vary as the number of distribution facilities changes? Certain costs, e.g. administrative

overhead, will be fixed, regardless of the size of the facility. Other costs, particularly those related to inventory, will exhibit economies of scale. For example, the so-called square-root law hypothesizes that inventories at warehouses increase as the square root of the sales covered by the stocking location. While there are economies of scale in inventories, empirical studies indicate that the precise relationship varies with the business, and that, in general, that, inventories will vary with a power of sales between .5 and 1.0 [7]. A higher power indicates a higher degree of correlation across geographic areas. In this case the splitting of inventories across several distribution facilities does not substantially increase total inventories. Other costs will be simply proportional to the total sales volume. Labor costs will presumably be proportional to total sales volume, as each unit of merchandise will require the same type of materials movement, regardless of how long it sits on the shelf.

In summary, inventory and other facility costs (not including those costs that are proportional to sales volume) will be fixed for each location or will vary as a power of sales between .5 and 1.0. That is,

$$C = A + KS^B$$

where

C = inventory and facility costs

A = fixed costs

K = constant

S = sales level

B = constant

As the number of facilities increases, the cost per facility decreases, but the total costs increase.

These types of general relationships can be used to develop conclusions on the best number of distribution facilities and the tradeoffs between costs and service. For example, with outbound costs paid by the manufacturer, transportation costs decrease but facility costs increase as the number of facilities increases. (This assumes inbound transportation costs, or those from plant to distribution facilities, remain approximately constant, while outbound transportation costs decrease as customers are generally closer to the nearest distribution facility). With fixed-facility costs low (i.e. total costs are proportional to a power of sales) a mathematical relationship can be derived showing that the best number of distribution facilities is proportional to a power of total sales volume between 0 and .5. (The power is 0 when facility costs are proportional to sales volume, in which case there is no premium for splitting volume among several facilities. A power of .5 results when facility costs vary as the square root of sales volume.)

If a firm doubles its volume, for example, it should increase the number of its distribution facilities between zero and 41%. The curve relating total costs and the number of facilities (see figure 1) will be relatively flat around the region of the optimum, but the approach indicates the nature of the relationship between the number of facilities and sales volume.

Perhaps a more important question than cost minimization is the relationship between the distribution costs and customer service, defined as delivery time, as the number of facilities is varied. Assume now that outbound costs are paid by the customer. Hence as the number of facilities is increased, the costs increase, but outbound delivery time varies as $N^{-\frac{1}{2}}$. Since both costs and outbound delivery time can be

expressed in terms of N; N can be eliminated and distribution costs can be related to outbound delivery time T.

We do not present this derivation but note that the term in this relationship between the costs of distribution and the delivery time is proportional to T^{-2+2B}, where T is the delivery time and B is the exponent in the power relationship (1) between inventory and other facilities costs and sales volume. For example, if inventory costs are proportional to the square root of sales, then costs are inversely proportional to deliver time. The result is a wide range of cost-delivery time relationships on the efficient frontier, or the most cost-efficient distribution system for a given level of service. The general form of this tradeoff relationship can have a significant impact on industry logistics structure [2]. Industries with relatively flat curves may offer more feasible alternatives for the various firms in the marketplace than industries with relatively sharp turns. In the latter case firms not locating at the point of curvative may offer significant premiums either in cost or delivery time. In the former case firms can offer alternative service levels for modest differences in cost. (See figures 2 and 3).

The important issue for number of distribution facilities is the impact of the inventory-sales parameter B in (1) on the cost-delivery time tradeoff curve. Figure 4 presents the curves for two different values of B. For the higher B case of .875, there is higher correlation among regions of the country, and splitting inventories among locations does not significantly increase costs. Indeed, the B = .875 curve is flatter over a wider range of delivery time values, until it becomes sharply kinked at low values of delivery time, or very fast delivery time. Consequently, the nature of demand and facility economies of scale will affect the shape of the curve and, in turn, the structure of the industry. In industries

with higher B, firms will generally have many distribution facilities, while in industries with lower B, there may be a wide range of number of facilities.

3. Location and Size of Facilities

Sizing and locations questions primarily consist of the following

- How large are appropriate facility territories?
- How sensitive is total market share and costs to location and size?
- How are locations identified as the firm grows

Given a territory, a distribution facility location will be based on transportation costs and customer proximity. The size will be simply the size required to service the territory. The demand centroid of the facility, the location that minimizes the weighted average distance to demand points, will minimize average customer proximity and, assuming transportation costs are proportional to distance, the transportation cost. The centroid can be approximated either by weighted coordinate average or a coordinate median.

Determination of facility territories can be solved on the basis of minimizing average distance to the nearest distribution center or warehouse. Generally, this also minimizes transportation cost and delivery time. For areas of high cost (or delivery time) per mile, distances should be more heavily weighted.

Intuitively, where demand is denser facility territories should be smaller, but total demand covered by the facility should be larger. Hence the size of the facility should vary inversely with a power of demand density between 0 and 1. The precise power is 2/3 [7]. Hence facility territory sizes will decrease by a factor of 4 and total facility, demand will double if demand density increases by a factor of 8.

To best illustrate the sensitivities and growth questions, we present a case study. The study illustrates some conclusions that are applicable

to many situations. The company involved was a major Eastern retailer embarking on an ambitious growth program. Service requirements and the economics of transportation consolidation pointed out the need for additional distribution centers. Three different scenarios for chain size were of concern: the current chain, the fully expanded chain, and an interim chain.

Consolidation economics plays an important role for any logistics system involving deliveries from many origins to many destinations. With large numbers of paths of small loads, it is economical to consoldiate loads. The automobile companies, who procure goods from hundreds of vendors and deliver them to multiple assembly plants, and retailers, who need to transport merchandise from hundreds of vendors to large numbers of stores, are good examples of this. Perhaps the most striking example of this is Federal Express Corporation, who consolidates almost all of its deliveries at its main hub at Memphis, Tennessee.

The key questions for the retailer were

- The sensitivity of cost and service to the utilization of its existing facility, and

- The staging of expansion decisions within the firm's overall growth strategy

The utilization of the existing facility was important in that the company had a large facility in the eastern part of the country that could be expanded or reduced in size. Hence it was important to understand the sensitivity of costs and service to utilization of this facility in the long-term strategy of the firm. With respect to the second issue, the staging of decisions as part of the growth strategy, it was important to understand how the firm could expand while at the same time controlling distribution costs and services.

To analyze the issues, the author developed a computer model to optimize product flows within the distribution network given the utilization of each of the distribution facilities. Figure 5 presents the relationships between costs and utilization of the existing facility for alternative networks of two distribution centers. The upper curve represents a network with the Eastern location and a fixed midwestern location. The lower curve represents network with the Eastern location and the best second location (which will vary as the utilization of the Eastern facility changes).

As the utilization of the existing facility increases, the best second location moves further away, and the cost of a network with a fixed second location can rise very sharply. The analysis shows that locations of facilities as well as costs can be very sensitive to utilization of given facilities.

The set of optimum distribution networks for different points in time during the growth stage of the firm identified the best implementation strategy for new distribution centers. It turned out that best second location for the interim point of the rapid growth stage was 1) the best second location for the fully expanded chain and, 2) a part of the best network with three distribution centers. While this result was somewhat fortuitous, it supports the concept that a firm should expand into new geographical areas sequentially (a fanning out process) rather than expanding simultaneously to all projected markets. The latter approach can lead to diseconomies of scale in distribution, as such an approach will yield large geographical areas with small volumes, while a sequential expansion might be achieved economically in terms of distribution costs.

4. Deployment of Inventory within a Multi-echelon Inventory System

The third key issue in the design and control of a multi-location distribution network is inventory deployment for a multi-echelon system. Each echelon or stage feeds the succeeding stage within the network. While the five or six stage systems for field service in many high-tech businesses are in the minority, many firms operate a large number of distribution facilities. Since the limited number of manufacturing locations invariably act also as stocking locations, these distribution systems are defacto two-echelon inventory systems. The situation is depicted in figure 6.

The deployment of inventories between the two stages of the systems is a complex question. Indeed, when one starts investigating alternative methods of deploying inventories in a two-stage system, there are very different implications for facility capacities and buffer stocks. In general, there are two sensible methods for deploying inventories between the two echelons of the system. One method concentrates inventories at the central location or locations (a central system), while the second method concentrates inventories at the second stage, or the satellite locations of the system (a satellite system) [8]. With a central system, the satellite warehouses carry stocks to protect against lead time only, while the central location or locations carry large buffer stocks to protect against the production of procurement lead time. With a satellite system, the satellite warehouses carry larger buffer stocks to protect against both transit and production lead time. Under this type of approach, the warehouses associated with the central plant or plants act mainly as a staging and marshalling areas for consolidated shipments to the satellite warehouses.

In a satellite system, merchandise is pushed (or pulled) out to the satellite locations as much as possible. In a central system, some inventory

is held back for protection, thereby reducing requirements at the satellites to a significant degree. The exact inventory levels can then be based on standard approaches for calculating buffer stocks given the appropriate lead times (transit time for the satellite locations and the production time for the central location). Obviously, the type of organization and information system will affect the relative desirability of the two types of systems. Each type of deployment strategy will require a specific type of control system, which is discussed in the next section.

Theoreticians have not been able in general to characterize the best inventory deployment strategies for these multi-echelon systems. However, the only two reasonable options are the two deployment strategies outlined above. The choice between the two options, moreover, can have an enormous impact on facility requirements. This latter point is also best illustrated by a case study. The author was involved in a location study for a major consumer goods manufacturer. At the time of the study, the East coast factory and warehouse serviced 80% of the country, and the west coast satellite serviced 20% of the country. The purpose of the study was to evaluate and recommend additional locations for warehouses.

One of the keys to the analysis was that the product was a high-value, low-weight product for which inventory costs were dominant. It became clear fairly early in the analysis that the distribution cost analysis would require identification of the specific inventory deployment strategy. We then simulated the inventory levels of each and every product of the company for both a central and satellite inventory deployment strategy.

The results of the simulation are presented in Table 1. Note that while the net inventories of the two approaches are not vastly different, there are very different allocations of inventory. These allocations will require

different facility capacities and are hence critical in the development of a strategic distribution plan.

Which of the two types of approaches should be adopted generally? There is no direct answer and each of the two approaches must be evaluated separately. Table 2 shows which system is favored for several different characteristics of the system [9]. The analysis of many of these factors can be based on a very general principle of inventory management: hold inventory before the high value-added step. That is, if delivery to the final echelon is a high value-added step in terms of all costs, hold the inventory centrally in the central system. This principle can be illustrated by its application to the characteristic of the number of remote warehouses. With a large number of remote warehouses, the final echelon in aggregate adds a great deal of value, through additional inventory, to the product. It is hence beneficial to store this inventory before the high value-added step in a central system. A large number of remote warehouses hence favors a central system.

5. Control of Inventory in a Multi-Echelon System

Multi-stage distribution systems pose issues of inventory control as well as deployment. The dependencies of demand, for example, from satellite locations to central locations, require more sophisticated types of control than the simpler types of approaches for single locations. In the past several years, Distribution Requirements Planning, or DRP, has been proposed as an appropriate means of controlling inventory within a multi-echelon environment. DRP uses demands, either actual or forecasted, at the satellite locations to determine replenishment requirements at the satellite locations, and in turn to determine a requirements schedule at the central location or locations. The approach, like its manufacturing analog materials requirements planning, or MRP, uses a requirements schedule to develop a precise schedule of production and procurements at the central location.

DRP is designed to deal with some of the problems of coordination between central locations and saellite locations in a multi-echelon system. DRP, however, is not always the system of choice for all multi-echelon systems. For two-stage systems, the most typical system for a manufacturing firm, there are actually three different approaches for inventory control:

Separate simple systems

DRP

Allocation control

Separate systems involve separate control systems for each location. Order-point control is the most typical. In this type of approach, each location controls its inventory independently using order points and order quantities characteristic of single-location inventory systems. When there are significant interactions among locations, for example when several satellite locations simultaneously make large orders, an order-point system can lead to

problems. DRP is designed to deal with these problems through better scheduling of requirements at the central location.

Simple control systems such as order-point systems, however, can also be formulated in terms of echelon inventories as well as in terms of inventories at the specific location, which are referred to as installation inventories. An echelon inventory consists of the inventory at a single installation as well as all of the inventory at succeeding locations. For a two-stage system with a single central warehouse, for example, the echelon inventory for the central location consists of the entire inventory in the entire system. Replenishment at the central location would therefore be based on total system inventory. This type of approach when associated with perpetual target inventories, is also known as a base stock approach and can alleviate some of the problems of a simple order-point systems.

The final type of control system, the allocation control system, is based on the concept of simultaneously replenishing groups of satellite locations. When such a joint order reaches the central warehouse stage of the network, it is allocated and pushed out to the satellite locations as expeditiously as possible. The central location acts as a staging area and hence the system is designed for a satellite inventory deployment strategy.

The best choice of inventory control for a multi-stage system depends on the means of inventory deployment and other characteristics. Table 3 presents the control system appropriate for the three main scenarios of two-stage inventory systems. For a satellite inventory deployment system, the central locations are by definition staging areas and inventory is pushed out to the satellite locations. An allocation system is appropriate here. For a central

inventory deployment system with a moderate number of satellite warehouses, there are significant dependencies between the demands of the satellite warehouses. This requires a high level of coordination in replenishment. While a base stock system can be designed to deal with this, a DRP system is clearly the system of choice. However, with a central inventory deployment system with a large number of satellite warehouses or with small satellite warehouses, demand at the central warehouses achieves a certain level of stability. For example, no single warehouse will make batch orders that will dominate demand at the central location or locations. When demand at the central location is stable, the advantages of DRP are reduced, and a system such as order-point control is sufficient.

With a hundred satellite locations with independent demands, for example, it is not neccessary to tabulate detailed forecasts of satellite orders. There is a certain statistical but stable pattern of demand at the central location, and the control parameters of the inventory control system can be adjusted for this pattern.

The important issue for inventory control is that as service, through additional facilities, is improved, there is a certain level of coordinated control of inventories that is required. As a firm expands from a single distribution facility or a small number of independently operated facilities, simple control systems must evolve to more sophisticated ones.

6. Conclusion

there are a large number of issues to address in the design and development of a manufacturing and distribution network. This article attempts to identify some of the key issues in the distribution part of the network. While there is no one prescribed method of system design and control, businesses should be aware of

- the tradeoff between cost and service and their sensitivity to the number of facilities
- the desire for smaller territories but higher volume coverage in areas with greater demand density
- the sensitivity of costs and locations to existing capacities during the firms growth phase
- how inventories can be allocation between echelons
- the importance of more sophisticated control in an expanded network.

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11. See Rosenfield and Pendrock for an explanation of each.

Table 1

Simulation for Central and Satellite Inventory
Deployment Strategies

Inventory in MM $

	Central	Sat. 1	Sat. 2	Sat. 3	Total
Central Strategy	9.50	1.05	1.08	.51	12.14
Satellite Strategy	4.41	2.47	3.31	1.53	11.72

Table 2

Factors Favoring Central or Satellite System

Factor	System Favored as Factor Level Increases
Value Added	Central
Number of Remote Warehouses	Central
Transit Time	Satellite
Procurement Time	Central
Demand Correlation among Regions	Satellite
Transshipment Costs	Central
Sales Level	Satellite

Table 3

Inventory Control Strategies Appropriate
for Different Scenarios

Deployment Scenario	Best Control System
Central with numerous satellites	order-point
Central with limited number of satellites	D.R.P.
Satellite	Allocation

Figure 1

Distribution Costs

Versus

Number of Facilities

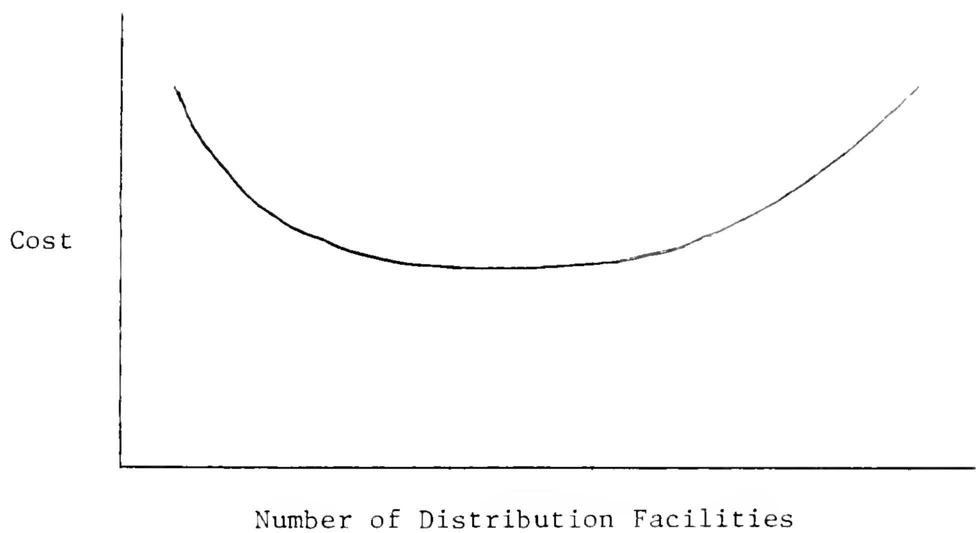


Figure 2

Relatively Flat Cost-Delivery

Time Tradeoff Curve

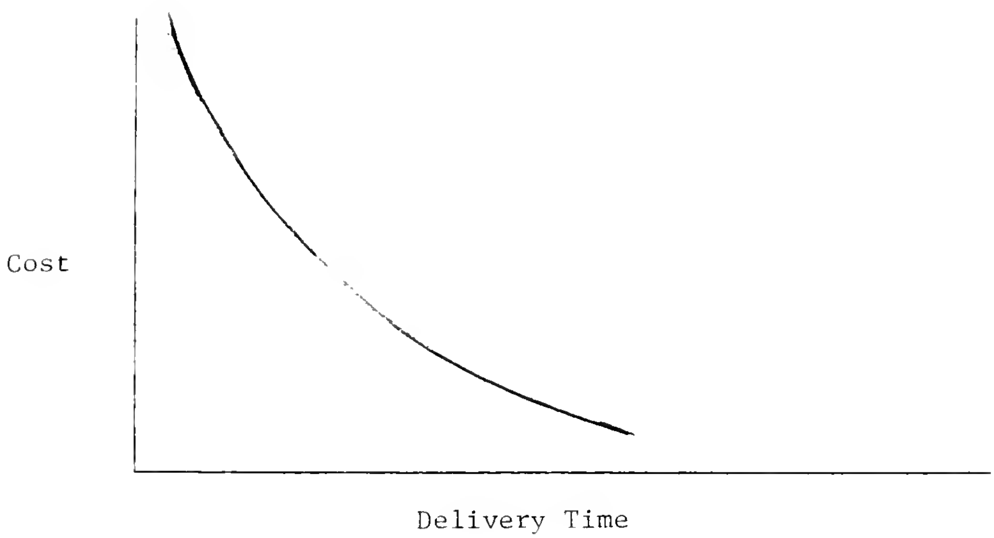


Figure 3

Cost-Delivery Time Tradeoff

Curve with Sharp Curvature

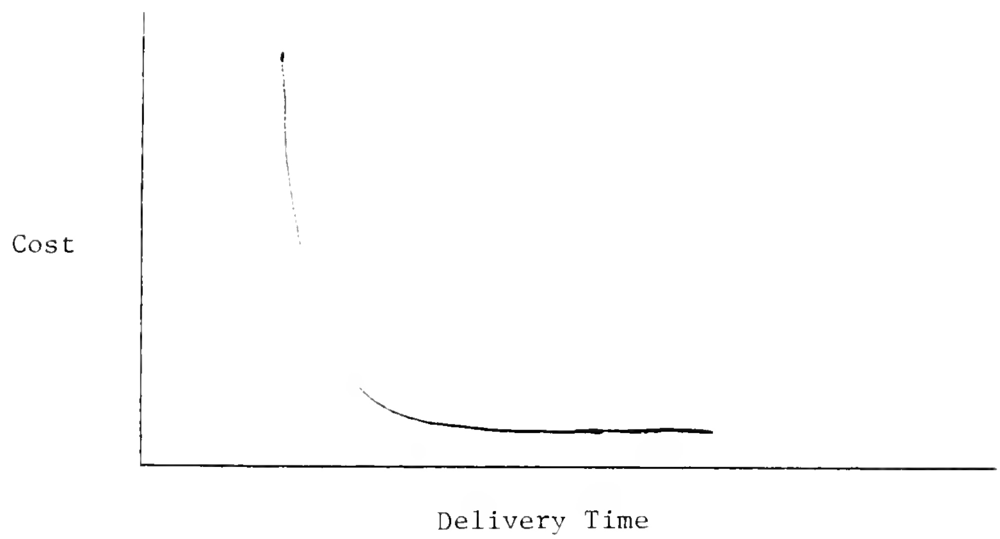


Figure 4

Distribution Cost-Delivery Time

Curves for Alternative B

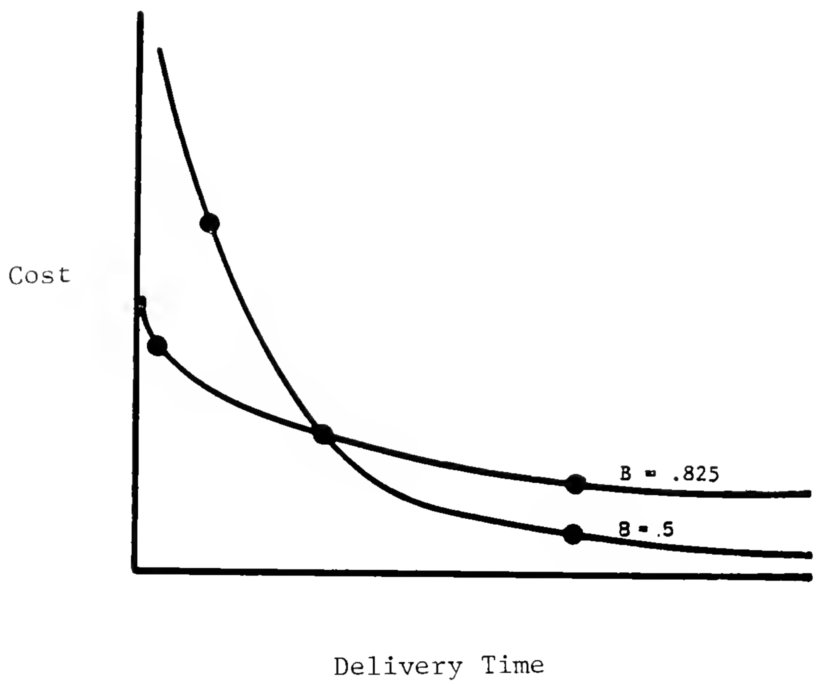


Figure 5

Cost versus Capacity Utilization of Eastern Distribution Facility

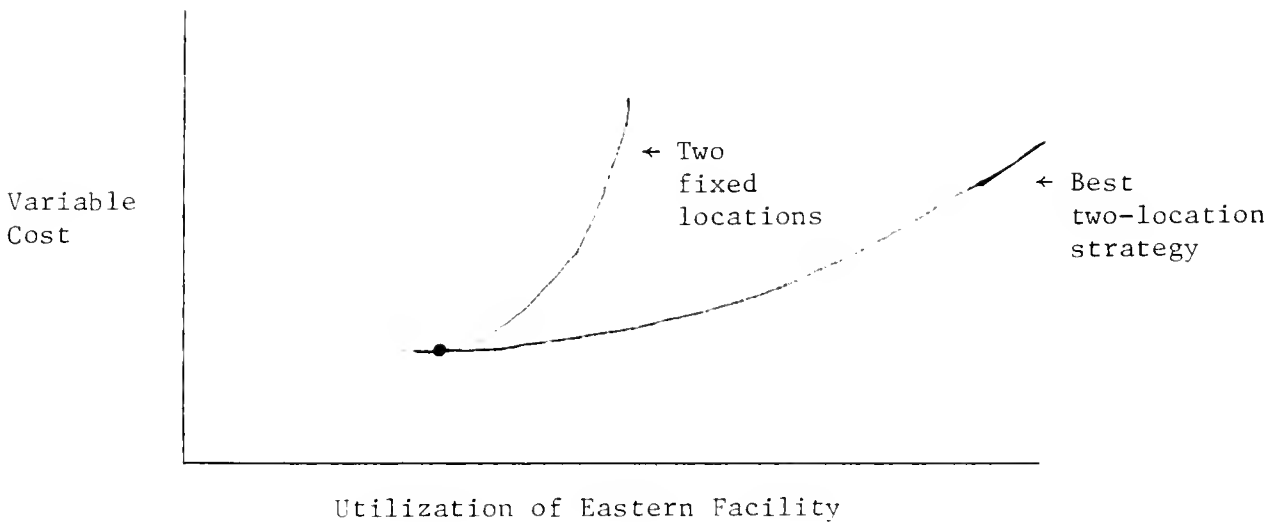
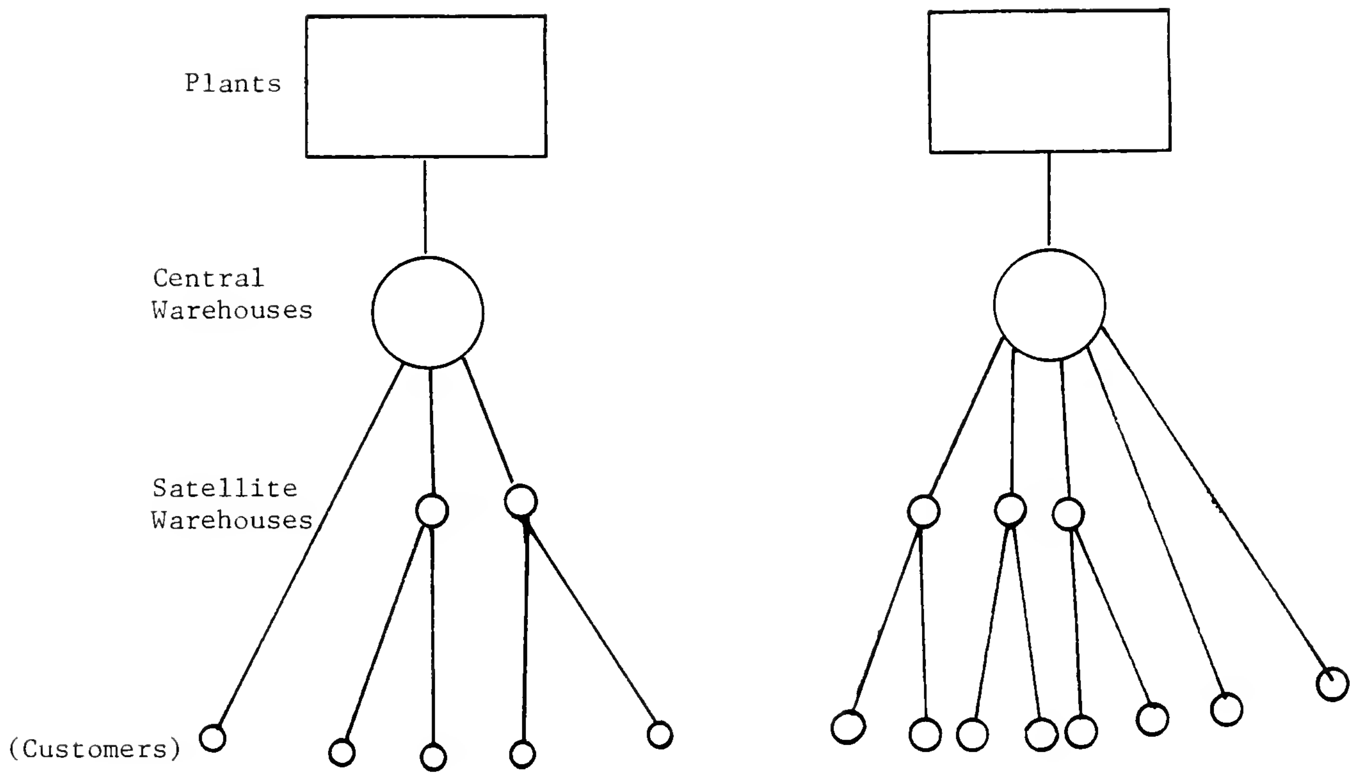


Figure 6

Two-echelon Inventory Systems
Typical in many Businesses



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